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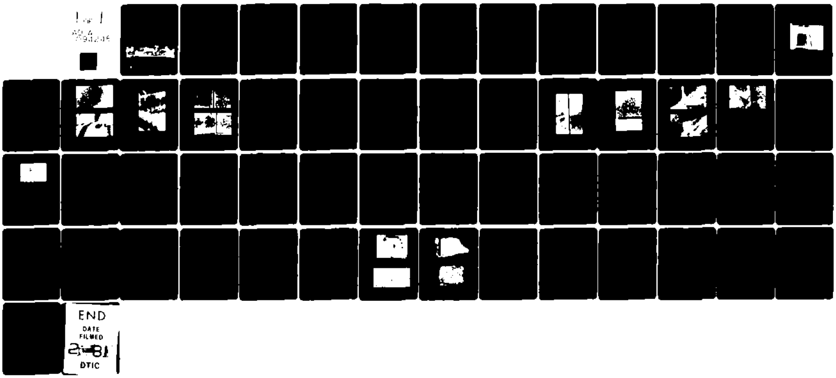

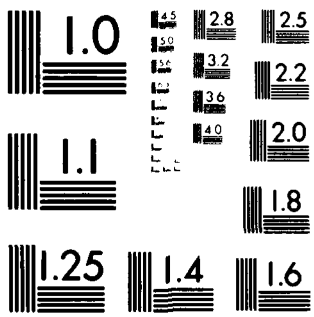

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LEVEL II

MISCELLANEOUS PAPER SL-80-19

CONCRETE DETERIORATION IN SPILLWAY WARM-WATER CHUTE RAYSTOWN DAM, PENNSYLVANIA

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The concrete in the walls and floor of the warm-water chute of the spillway of Raystown Dam, a relatively new structure (less than 10 years old), was showing an excessively rapid deterioration in quality. Surface concrete appeared extremely sandy and rough, resulting from an apparent dissolving away of cement paste and coarse aggregates. In addition to the surface problems, the walls separating the warm-water chute from the main spillway chutes contained interconnected voids, allowing water to flow under and through the walls. Several of these voids were large enough to reach inside. (Continued)

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20. ABSTRACT (Continued)

A limited sampling program provided concrete cores, aggregate, water, and efflorescence samples for chemical and petrographic analysis. A review of the pH history of the water in the reservoir was also conducted.

The petrographic examination revealed that the surface concrete had been attacked by an aggressive liquid. Calculation of the Langlier Index for the reservoir water showed it to be aggressive to concrete. The pH history and the lack of evidence of introduction of acid into the reservoir, coupled with the chemical and petrographic evidence, led to the conclusion that the water itself was causing the surface damage.

The voids in the walls were attributed jointly to poor consolidation of the concrete and design details which allowed the aggressive water access to the interior of the walls.

This is believed to be the first reported case of aggressive water attack on a concrete structure in the United States.

PREFACE

The investigation described in this report was conducted for the U. S. Army Engineer District, Baltimore, by the Concrete Technology Division (CTD) of the Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES). Authorization for the investigation was given in DA Forms 2544 dated 13 August, 12 September, and 12 October 1979.

The investigation was performed under the direction of Messrs. Bryant Mather, Chief, SL, and John M. Scanlon, Jr., Chief, CTD. The site inspection was by MAJ Terence C. Holland, CE. The chemical analysis was by Mr. Tony B. Husbands. The petrographic examination was by Mr. G. Sam Wong. The report was prepared by MAJ Holland and Messrs. Husbands, Wong, and Alan D. Buck.

The cooperation of Mr. Arthur Fleetwood of the Baltimore District is greatly appreciated.

Funds for the publication of this report were provided from those made available for operation of the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 42.

The Commander and Director of WES during the investigation was COL N. P. Conover, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	1233.489	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic yard	0.5933	kilograms per cubic metre
square miles	2.589988	square kilometres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CONCRETE DETERIORATION IN SPILLWAY WARM-WATER CHUTE, RAYSTOWN DAM, PENNSYLVANIA

PART I: INTRODUCTION

Purpose

1. The investigation described in this report was undertaken at the request of and in cooperation with the U. S. Army Engineer District, Baltimore, in an attempt to determine the cause of excessively rapid deterioration in the condition of the concrete in the walls and floor of the warm-water chute of the spillway of Raystown Dam, Pennsylvania.

Description of Dam

2. Raystown Dam is located on the Raystown Branch of the Juniata River approximately 12 miles* south of Huntingdon, Pennsylvania (Fagerburg, 1979, and Corps of Engineers, 1979). It is a multipurpose project providing flood control, downstream flow augmentation, and recreation. The dam, which consists of a rock and earthfill embankment section and a concrete control structure, was constructed between 1968 and 1973. Raystown Lake, impounded by the dam, is the largest lake located entirely within the Commonwealth of Pennsylvania. Additional information describing the lake and dam are in Table 1. Figure 1 shows an overall project site plan.

3. The concrete control structure consists of two 45-ft-wide ogee sections controlled by tainter gates. There is also an 8-ft-wide chute between the two main chutes of the spillway. This center chute is used to selectively discharge water from different elevations within the lake to regulate water temperature downstream and is referred to as the warm-water chute. A rectangular tunnel passes through the structure to

---

* A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 3.

Table 1

Characteristics of Raystown Lake and Dam*

Dam	
Type:	Rock and earthfill
Length:	1700 ft
Height:	225 ft above streambed
Gates:	Three total; two at 45 ft wide, crest elevation 768.6;** one (warm water) with discharge from elevation 766.0 or 750.0.
Construction period:	1968 to 1973
Lake	
Storage:	Recreation - 514,000 acre-ft Flood control - 248,000 acre-ft
Pool length:	Recreation - 30 miles Flood control - 34 miles
Shoreline:	Recreation - 118 miles
Flood control area:	960 sq miles

* Fagerburg, 1979, and Corps of Engineers, 1979.
** Elevations in feet above mean sea level (msl).

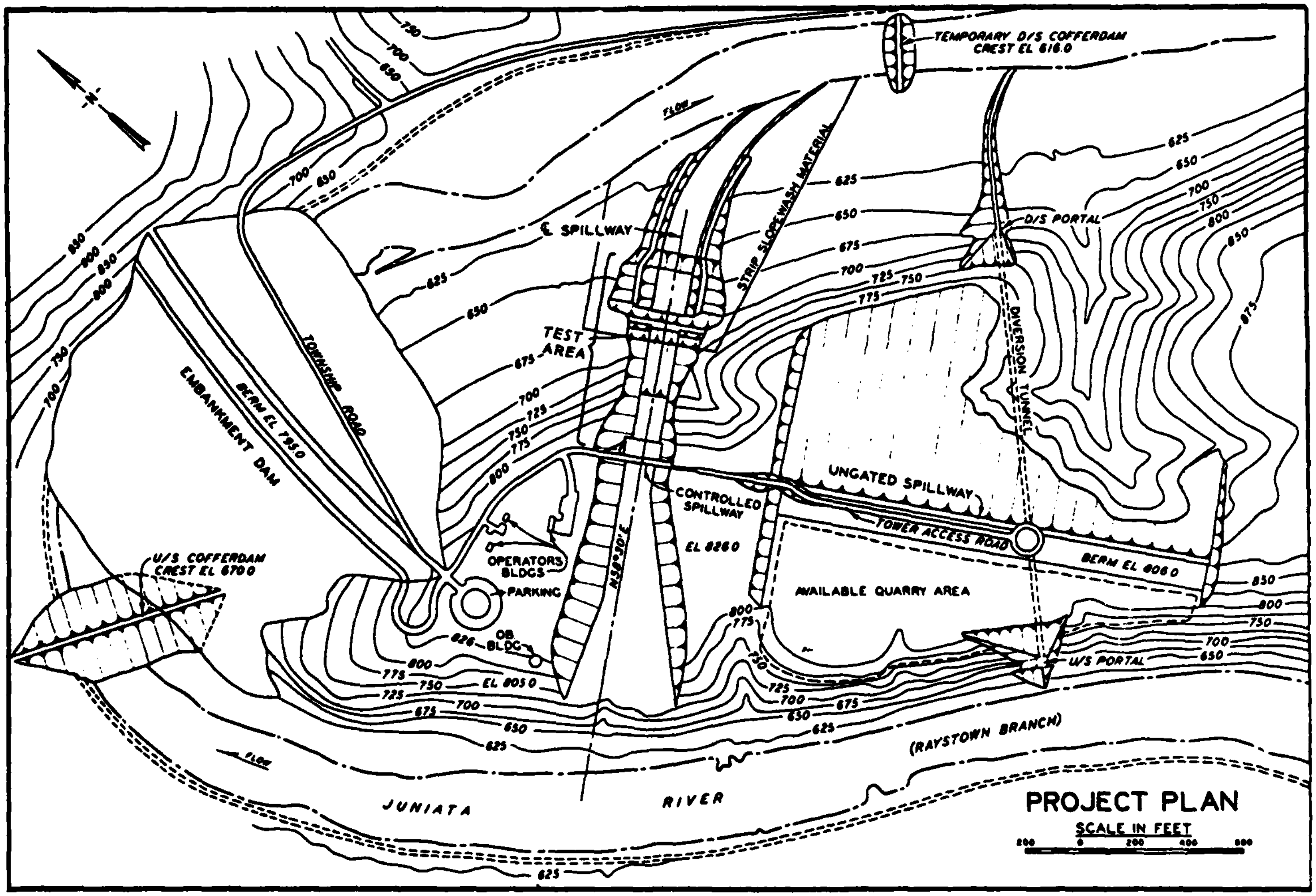


Figure 1. Site plan, Raystown Dam (from Fagerburg, 1979)

deliver water to the warm-water chute. Discharge through the warm-water chute is the normal operating mode of the dam for the majority of the year. Figure 2 shows the control structure and the three spillway chutes.

Description of Problem

4. In July 1979, the U. S. Army Engineer District, Baltimore requested assistance from WES concerning the deterioration of concrete in the warm-water chute. A site visit was made on 28-30 August 1979, attended by Messrs. Arthur Fleetwood and Clinton Anuszewski, Baltimore District, and MAJ Terence Holland, Concrete Technology Division (CTD), Structures Laboratory (SL), WES. The following description is based upon observations made during that visit and upon information received from the District since the site visit.

General condition of the structure

5. A brief inspection of the concrete in the control structure revealed no major deficiencies. Specific items which were noted are:

- a. Exterior concrete on the control structure appeared to be sound. Several minor cracks were noted in the bridge across the spillway gates.
- b. Steel pipe stubs embedded in the concrete near a machinery access door were holding water and rusting. These may cause surface concrete problems at a later date.
- c. There was a great amount of water and efflorescence present in the interior stairwell and gallery. The District is monitoring the amount of flow.
- d. One area of efflorescence was noted on the downstream face of the structure near the left abutment. The water causing this deposit is apparently flowing through the entire thickness of the structure.

Concrete in warm-water chute

6. The condition of the concrete in the walls, and to a lesser degree in the floor, of the warm-water chute is a marked contrast to that found in the remainder of the structure. The walls and floor are severely eroded and etched. There appears to be a preference on the part of the agent causing the damage for the removal of the carbonate

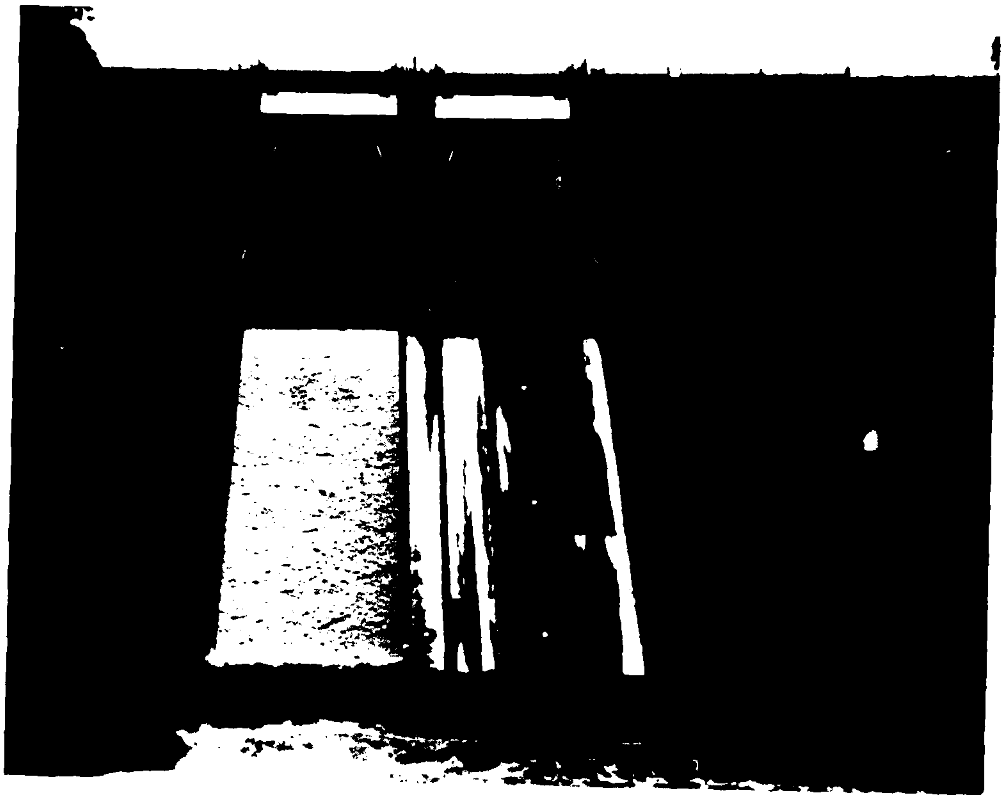


Figure 2. Control structure, Raystown Dam. The warm-water chute is the narrow chute in the center of the spillway

coarse aggregate. This leaves the siliceous sand grains in relief. A typically damaged section of wall is shown in Figure 3. Additionally, as can be seen in Figure 4, water is apparently flowing through or under the walls separating the warm-water chute from the main spillway chutes.

7. Following are detailed comments describing the condition of the walls in the warm-water chute (floor damage is described in para 8, below):

a. Damage near the mouth of the warm-water tunnel (i.e., upstream end of the chute) is noticeable for the full height of the wall. As one moves downstream, the damaged zone tends to reduce in height, but the severity of the damage increases in the lower portion of the wall. Typically, upstream, the lower portion of the wall (below the indicated waterline as shown by discoloration and algae) shows missing aggregate particles and numerous voids. The surface of the concrete is extremely sandy with little or no paste visible. Above the waterline, voids and bug holes (many are apparently a result of construction since the holes have a small exterior opening and a larger interior volume) are visible to the top of the wall. Figure 5 shows a wall section near the mouth of the tunnel. Figures 6 and 7 show close-up views of the damage in the upper and lower portions of the wall.

b. Moving down the wall toward the flip bucket, the waterline becomes closer to the floor, damage below the waterline increases in severity, the void zone remains visible above the waterline, and a zone of undamaged concrete becomes visible above the voids. Figure 3 shows the increased severity of the damage in the lower portion of the wall in an area near the flip bucket.

c. The surface of the walls appears to have been rubbed with a mortar coating after forms were removed. On areas where there is little damage, a sandy coating is visible with form marks (plywood impressions) visible under the coating.

d. Walls, particularly in the portion of the wall including and below the vertical curve of the spillway, are very wavy in the longitudinal direction, i.e., parallel to the flow of the water. This is apparently the result of inadequate bracing during construction. Vertical form joints are apparent every 4 ft. The waviness in the walls is approximately 3/8 to 1/2 in. in the span of 4 ft between form joints. The locations of the form joints appear also to have been filled with a mortar.

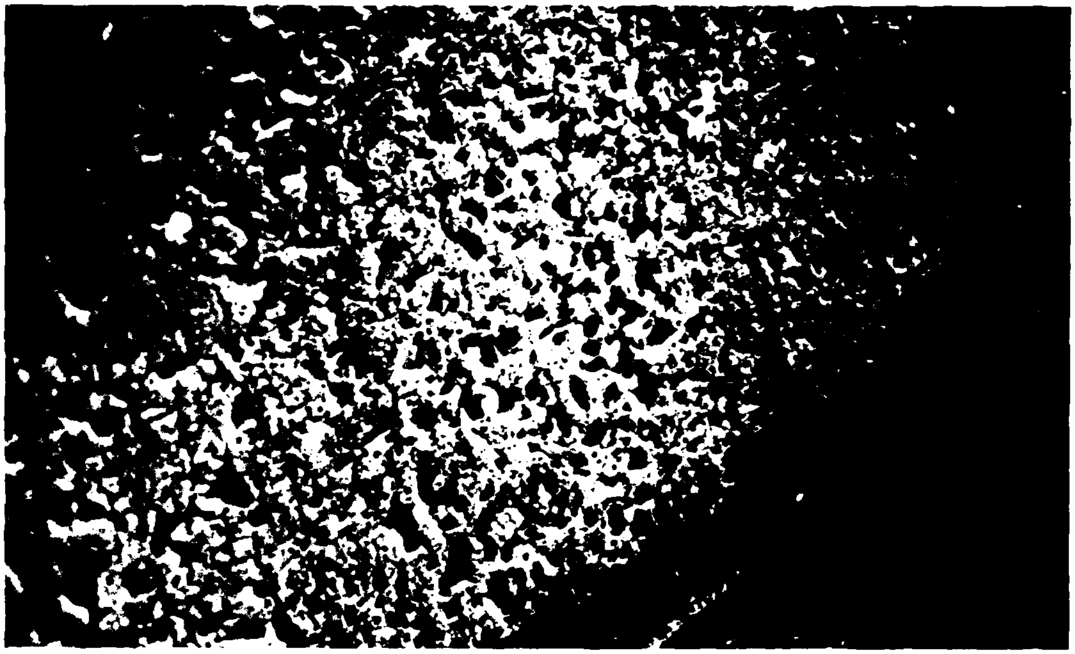


Figure 3. Typical damage to wall in warm-water chute. Flow is from right to left. This photograph is typical of damage found in the monoliths near the flip bucket

Figure 4. Water flow in warm-water chute. Note flow through or under the wall into the right main chute of the spillway near the flip bucket. Similar flow was seen through the left wall

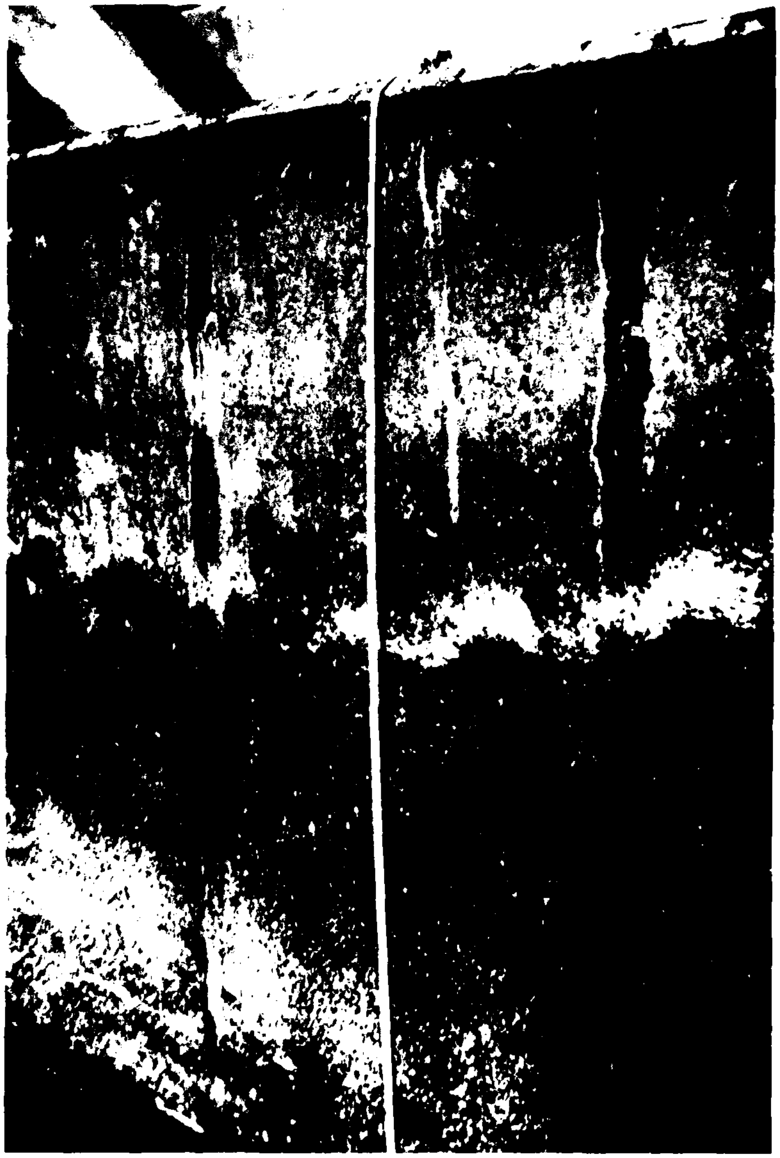


Figure 5. Full height section of wall of warm-water chute. Note differences in damage above and below the apparent waterline

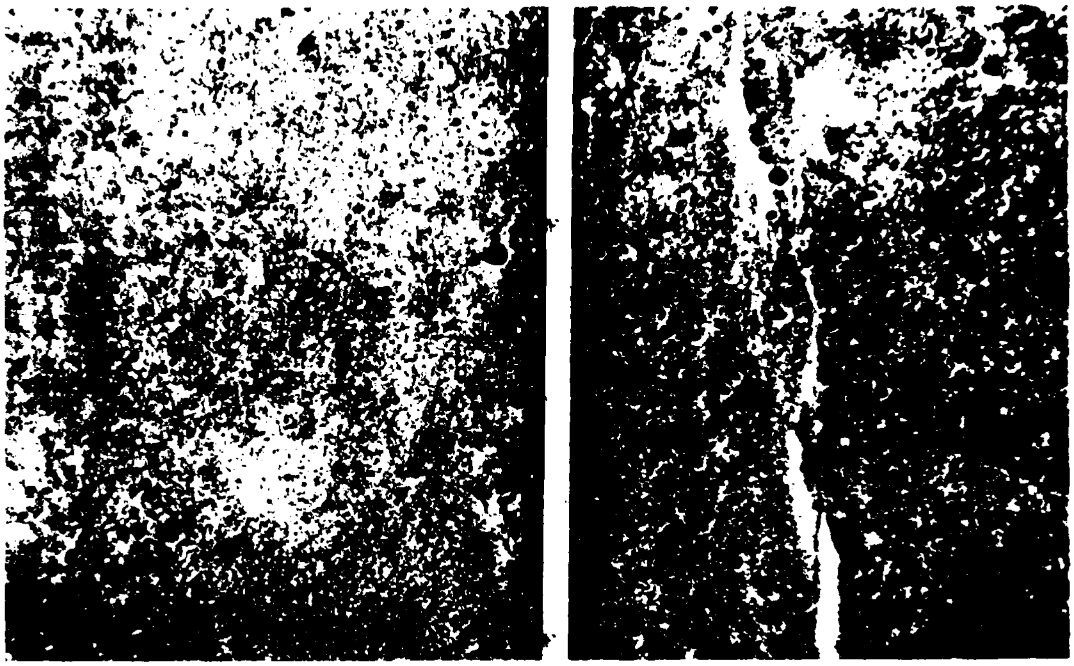


Figure 6. Closeup view of upper portion of wall shown in Figure 5. Note voids and "bug holes"

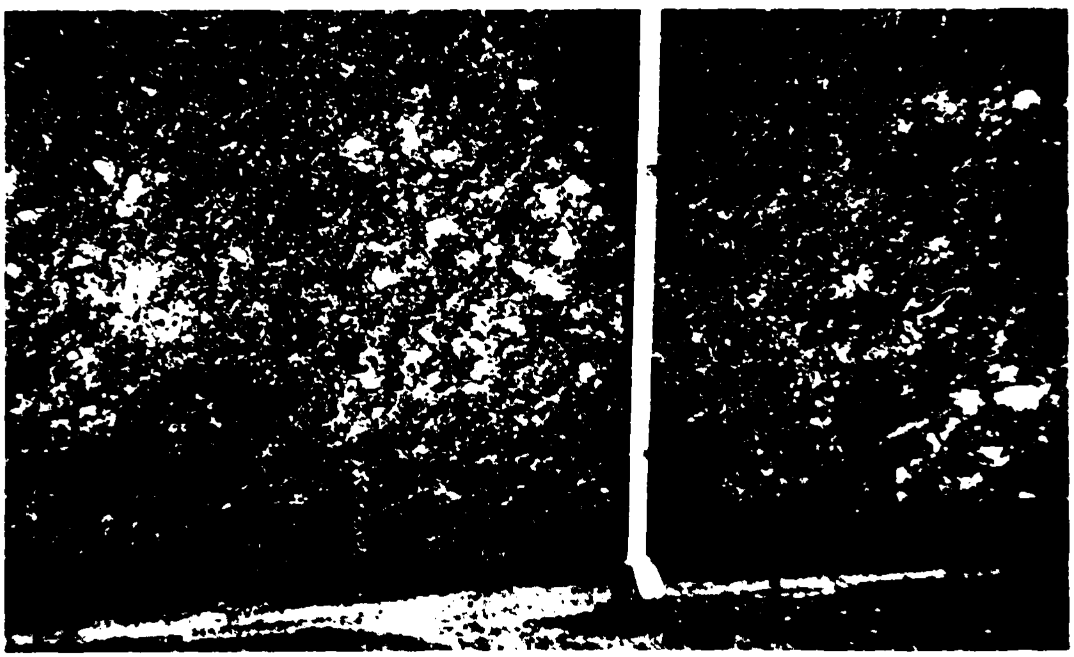


Figure 7. Closeup view of damage to lower portion of wall shown in Figure 5. Note sandy appearance and exposed coarse aggregate particles

e. The preformed material used in the contraction joints in the walls has deteriorated severely and has been pulled out of most of the joints.

f. Random sampling by hitting the wall with a hammer showed numerous zones of dull sounds, particularly in the lower 12 in. of the wall near vertical joints. Concrete in the lower 12 in. of the wall tended to crumble when hit with the hammer.

8. During the August 1979 site visit, a log of the damage in the warm-water chute was prepared. This log is presented in Table 2. Figures 8 through 13, which are referred to in Table 2, show monolith numbers and additional examples of concrete condition. The wall damage described above is not repeated in the table. The locations of cores taken and nondestructive testing (Windsor Probe and Schmidt Hammer) performed by members of the District staff during the visit are included in the table.

9. The results of the limited nondestructive testing performed at the site are presented in Table 3. The tests performed (Windsor Probe and Schmidt Hammer) are highly dependent upon the nature of the concrete surface.

Concrete in warm-water tunnel

10. The concrete in the warm-water tunnel was also inspected. In general, the damage noted was similar to that seen in the warm-water chute. The walls and ceiling of the tunnel were extremely rough, showing damage similar to that found in the lower portions of the walls in the downstream monoliths of the chute. The floor in the tunnel showed the most damage within the tunnel. Floor damage included coarse aggregate particles plucked out and coarse aggregate particles etched and exposed. The floor damage ended abruptly at the joint marking the downstream end of the tunnel. The abrupt end of the damage implies that there may be a difference in the concretes inside and outside of the tunnel or that the increased erosion within the tunnel may be a result of the hydraulic characteristics of the tunnel.

Concrete in left spillway chute

11. The concrete in the left main spillway chute was also inspected briefly. Several cracks with efflorescence were noted on the

Table 2

Log of Concrete Condition, Warm-Water Chute, Raystown Dam

NOTES

1. Distances were measured with tape on floor and are therefore not horizontal distances.
2. Directions (left and right) are in reference to facing downstream.
3. The right spillway chute was in operation with the gate open 12 in. when this inspection was made. It is probable that many of the joints on the left wall would have been wet had the left spillway been in use.
4. Monolith joints refer to both wall and floor joints which are co-located. Figure 8 shows a section view of the chute with monoliths numbered.
5. Terminology describing concrete condition conforms as closely as possible to ACI's Guide for Making a Condition Survey of Concrete in Service (ACI, 1968).
6. Damage to walls is not included in table. See para 8 of report.
7. Winsor Probe and Schmidt Hammer readings were taken as noted. Results are in Table 3.

Distance (ft)	Description
0.0	Joint - structure/monolith 1 (end of warm-water tunnel)
	Floor shows light scaling with a large number of small voids. Walls show typical damage.
13.3	Core No. 1. Chute is 80 in. wide at core. Center line of core is 34 in. from right wall.
17.5	Windsor Probe and Schmidt Hammer readings on left wall and slab.
21.8	Wall tapers to standard height (84 in.). Crack exists completely through wall on both sides approximately at location where wall changes section.
	From 13.3 to next joint, there is algae growth on floor and minimal damage. Walls typical.
42.7	Joint - monolith 1/monolith 2.
	Floor is covered with algae in this monolith. Little or no concrete damage. Walls typical.
84.7	Joint - monolith 2/monolith 3.

(Continued)

Table 2 (Continued)

Distance (ft)	Description
96.0	Windsor Probe and Schmidt Hammer readings taken on left wall and slab.
99.5	Core No. 2, left wall, 22 in. above floor.
105.7	Approximate center of metal velocity probe. Some paint still visible on the wall from velocity prototype tests.
	Floor in monolith 3 shows slight scaling with none to few voids and with some exposed and broken aggregate. More floor damage and less algae than monolith 2. Walls typical.
126.5	Joint - monolith 3/monolith 4.
	Core No. 3 was taken on floor across joint. Center of core was 26-1/2 in. from right wall. Right wall joint was making water.
	There is a noticeable difference in the condition of the concrete up and downstream of this joint. There is also a distinct change of section across the joint. The differing appearance of the concrete may be due to cavitation.
	Figure 9 shows this floor joint.
	Monolith 4 shows intermittent aggregate plucked from floor with an increasing amount of visible broken aggregate. Figure 10 shows typical floor damage. Walls are typical but height of damage is decreasing.
169.9	Joint - monolith 4/monolith 5. Wall joint making water.
	Floor in monolith 5 approximately same as monolith 4. Walls continue typical with decreasing damage above apparent waterline.
185.4	Large gouge in left wall 40 in. above floor, 5-in. diameter, 1-1/2 in. deep. Exposed aggregate and voids visible.
192.2	Approximate center of velocity probe. No change in condition of concrete surrounding probe.
215.1	Joint - monolith 5/monolith 6. Wall joint on right side making water.
	Floor in monolith 6 essentially same as monolith 5. Walls are typical with severity of damage increasing in the lower 3 ft (apparent waterline). For 1 ft above waterline shows very limited damage with many voids. Concrete above this zone appears to be sound with a sandy coating. Wall dusts in sandy portion when rubbed by hand.

(Continued)

Table 2 (Concluded)

Distance (ft)	Description
260.6	Joint - monolith 6/monolith 7. Joint making large amounts of water. Flow was great enough to be used as source of water for drilling cores downstream.
	Floor in monolith 7 continues the same. Lower wall damage is increasing with many voids and areas of missing aggregate being interconnected.
278.9	Water flow from void in wall on right (approximately 2 in. above floor).
283.3	Approximate center of velocity probe. Area 4 by 3 ft surrounding probe shows distinct increase in damage to the concrete with plucked and exposed aggregate (MSA 3/4 or 1 in.).
306.1	Joint - monolith 7/monolith 8. Right wall making water adjacent to joint (Figure 11).
	Floor in monolith 8 continues about the same. Wall damage is most severe in the lower 18 in. Wall damage is becoming more severe.
316.9	Horizontal crack on right wall approximately 4 ft long (wet). This crack appears to be a cold joint (Figure 12).
326.1	Possible cold joint, right wall. Pattern cracking between the two possible cold joints.
326.6	Gouge in center of floor, 9-in. diameter, 3-1/2 in. deep.
341.4	Additional pattern cracking in right wall.
347.7	Core No. 4 on left wall, 22 in. above floor.
350.0	Windsor Probe and Schmidt Hammer readings, both walls.
351.0	Core No. 5 on right wall, 22 in. above floor.
351.5	Joint - monolith 8/monolith 9. Severe damage on both walls adjacent to the joint on the upstream side. Holes are present which are large enough to reach inside (Figure 13). Aggregate sample obtained by reaching inside hole in left wall. Chunk sample also obtained from hole in left wall.
	Walls and floor in monolith 9 continue as above.
374.5	Approximate center of velocity probe. Distinct change in concrete in floor surrounding probe. A rectangle, 6 by 5 ft, centered on the probe shows severe scaling with 3-in. maximum aggregate exposed. This area shows much greater wear than other concrete in floor of this monolith.
396.9	Joint - monolith 9/flip bucket. Joint making water. Flip bucket was full of water and not inspected.

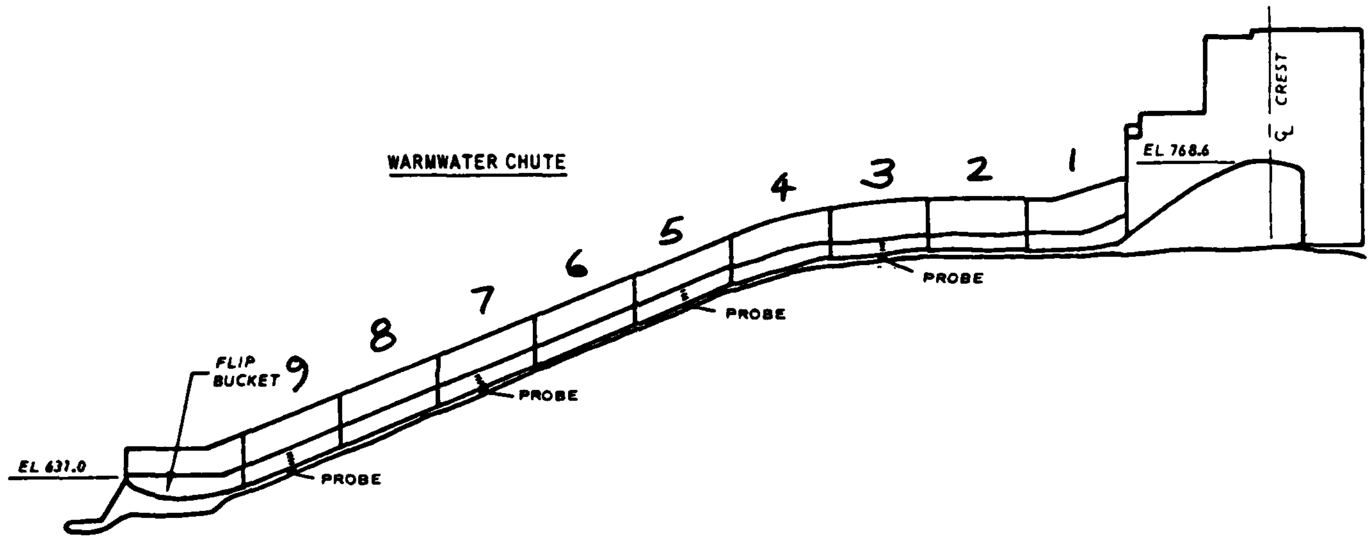


Figure 8. Schematic showing numbering of monoliths referred to in Table 2 (from Fagerburg, 1979)

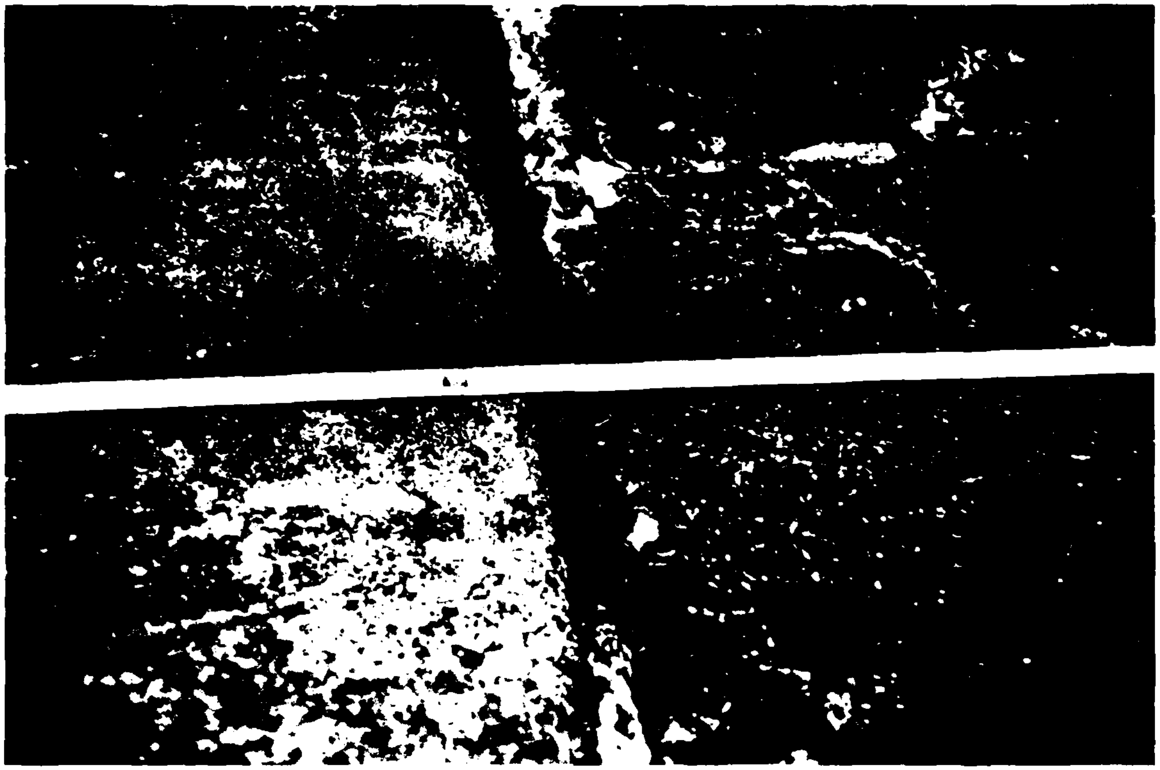


Figure 9. Floor joint, monolith 3/monolith 4. Flow is from left to right. Note difference in condition of concrete across joint

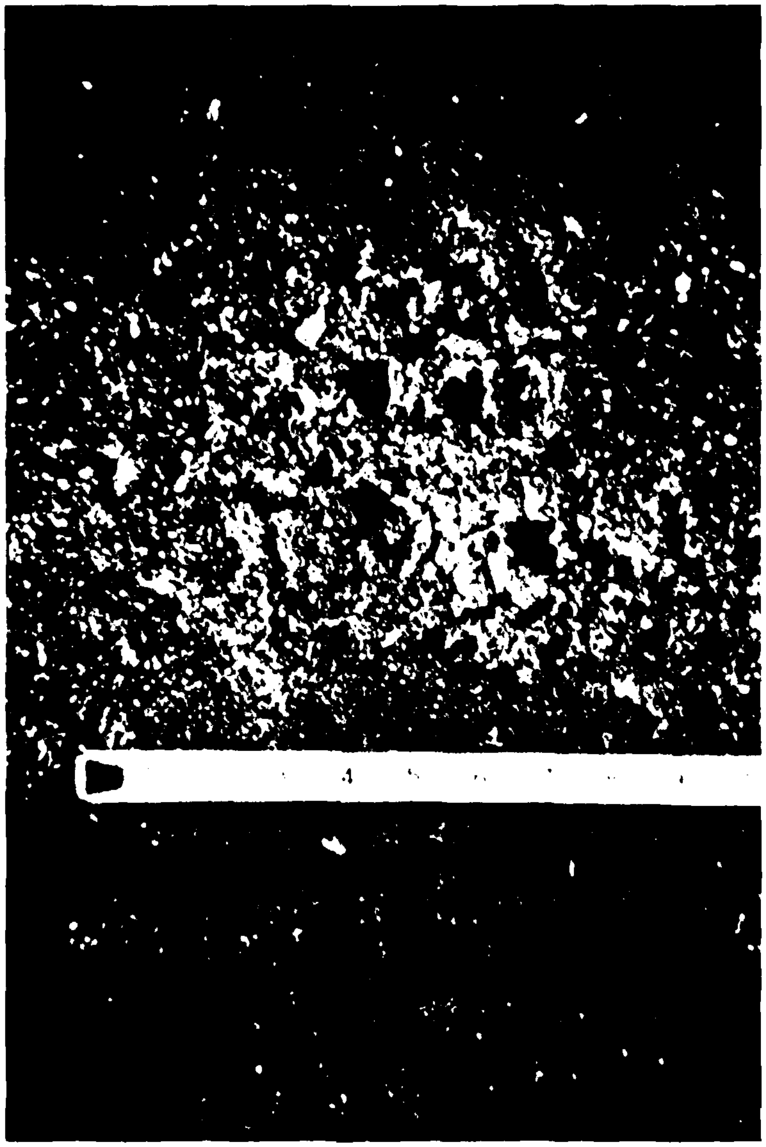


Figure 10. Typical floor damage showing missing and exposed coarse aggregate. This damage is typical of that found in monoliths 4 through 9

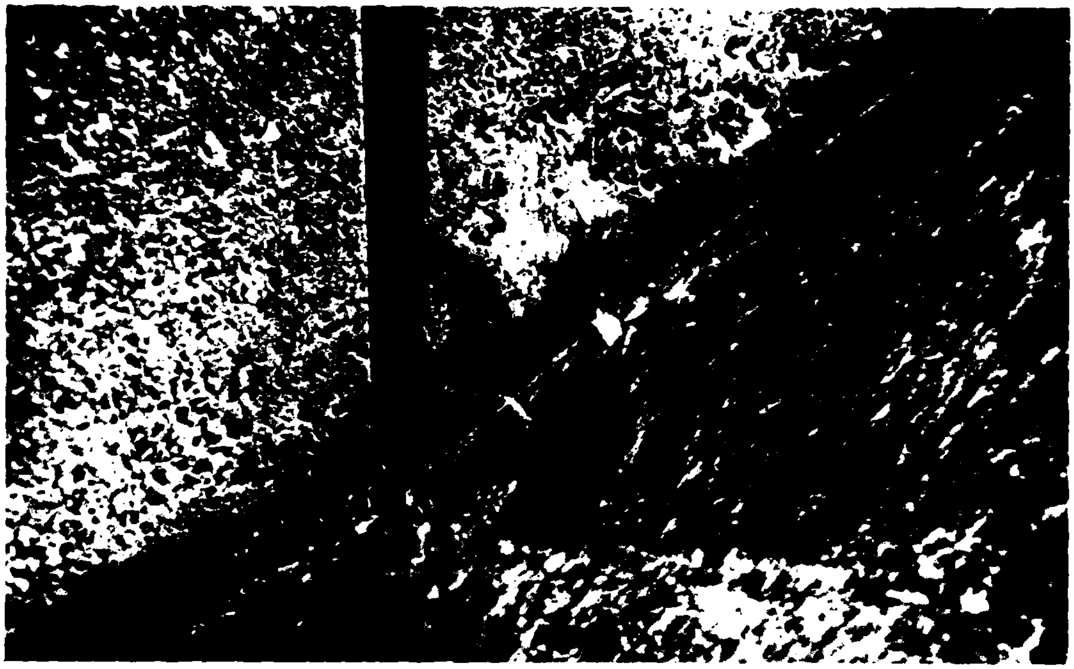


Figure 11. Right wall joint, monolith 7/monolith 8. Flow is from right to left. Note water flowing through/under wall and joint

Figure 12. Apparent cold joint, right wall, monolith 8

Figure 13. Large void in left wall, at joint, monolith 8/monolith 9. Void is large enough to reach an arm inside. Flow is left to right

Table 3

Results of Nondestructive Testing*

Monolith	Station**	Location	Schmidt Hammer Rebound (No.)	Compressive Strength (psi)	Windsor Probe Protrusion (in.)	Compressive Strength (psi)
1	17.5 ft	Left wall	--		1.90	5800
		Slab	19.5	1750	1.80, 2.37,†	5100,4600
3	96.0 ft	Left wall	31.5	4000	2.08	7000
		Slab	23.5	2400	2.08	7000
8	350.0 ft	Left wall	--		2.25	8200
		Right wall	16, 34	1750, 4500	2.00	6400

* Tests performed and data provided by Mr. Arthur Fleetwood, Baltimore District.
** Stations refer to system established in Table 2.
† Indicates low power setting. All other Windsor Probe tests were normal power.

spillway side of the wall dividing the left spillway from the warm-water chute. These cracks were not noticeable from inside the warm-water chute. The concrete on the spillway side of the wall showed some deterioration adjacent to the floor and at joints. The pattern of small visible voids was also present. Damage was much less advanced, probably due to the less frequent use of the main spillway chutes. Concrete in the spillway crest section appeared to be generally sound.

Samples obtained

12. The samples listed below were obtained at the site during the August 1979 visit. Analysis of these samples is described in Part II of this report.

a. Four pieces of coarse aggregate were obtained from the large hole at the base of the left wall upstream of the joint between monoliths 8 and 9 (Figure 13). Samples are shown in Figure 14.

b. Water. Two water samples were obtained for analysis. Sample 1: from upstream channel leading to structure, approximately 1 ft below surface; pH = 7.95; temperature 25°C. Sample taken by Mr. Pete Juhle, Water Quality Control, Baltimore District. Sample 2: downstream, across stilling basin from structure, same depth; temperature 24°C. Sample taken by MAJ T. C. Holland.

c. Efflorescence. A wall scraping was obtained inside the gallery which passes under the spillways. The sample was taken from the upstream wall under the right spillway by MAJ T. C. Holland.

d. Concrete cores. Five cores were taken (three from walls and two from floor of warm-water chute). Exact location of coring is in Table 2.

Wall construction technique

13. The contract drawings ("as-built") were examined to determine the construction requirements for the joint between the walls of the warm-water chute and the spillway slab. Approved shop drawings showing construction details were not available for review. The contract drawings show no details for the joint. It does not appear that the design requires monolithic construction. Neither does there appear to be a requirement for a waterstop at the joint. Examination of the joint inside the large void in the left wall in monolith 8 shows a formed

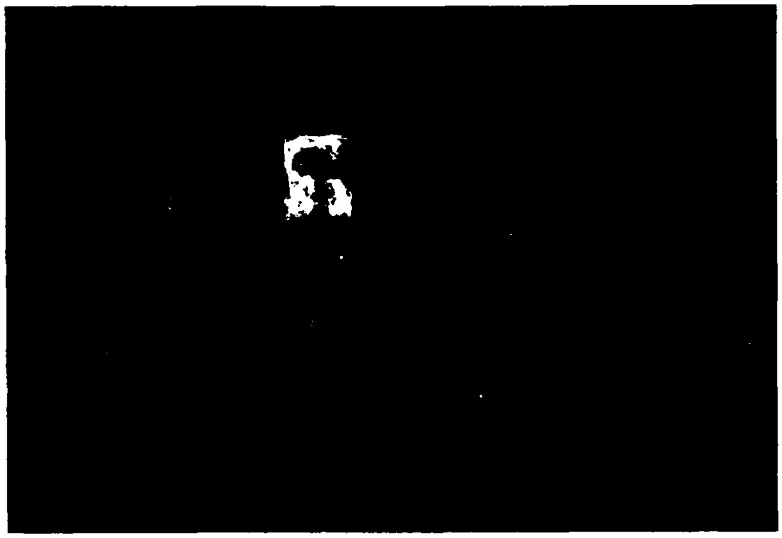
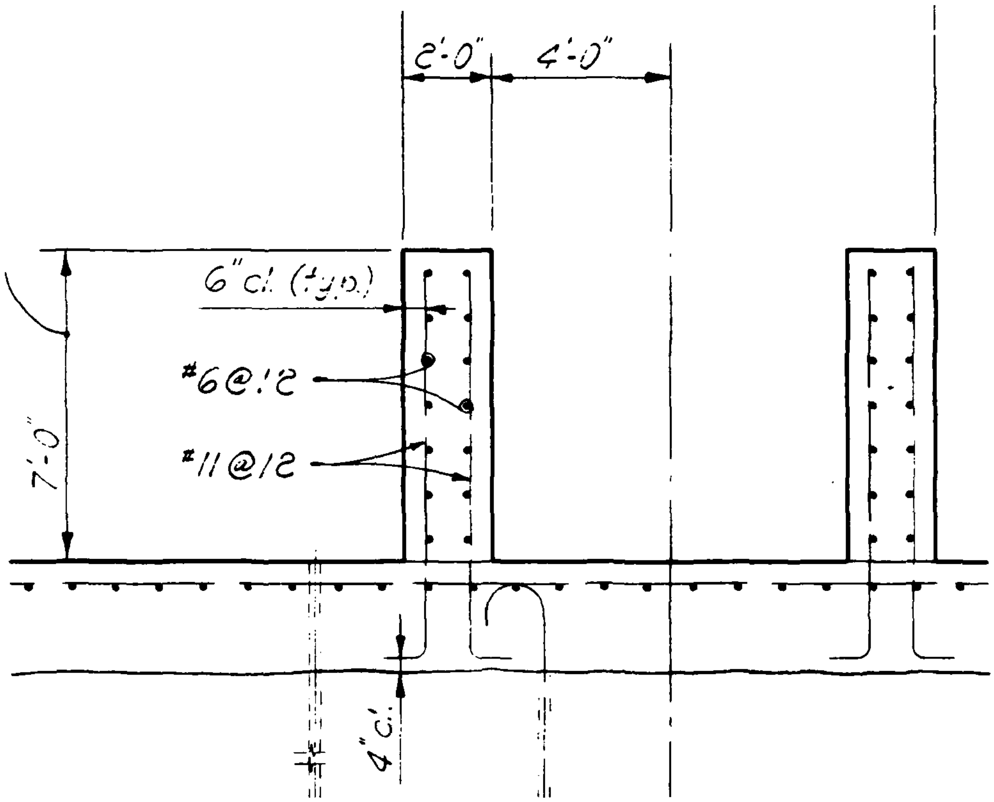


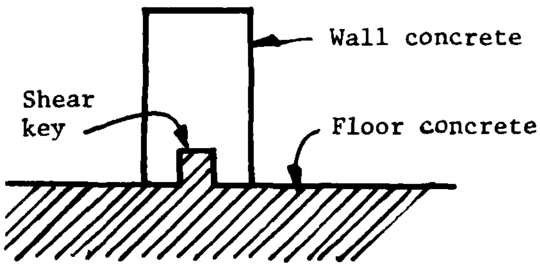
Figure 14. Aggregate samples obtained from void in wall of warm-water chute shown in Figure 13

surface which is apparently a shear key. Figure 15 compares the contract drawings and the actual construction. The construction technique as shown has allowed water to flow under and inside the walls of the warm-water chute.

14. The consolidation of the concrete in the walls must be considered. The most severe damage to the interior of the walls is located at the downstream toe of several wall segments. Due to the geometry of the placements, a small volume of concrete would have filled the forms very rapidly during the initial stages of the placement for each wall segment (Figure 16). The depth of the concrete would have increased quickly, making consolidation in the toe area difficult. With the exceptions of the water shown flowing through a void in the concrete in Figure 11 and the cold joint shown in Figure 12, exterior evidence of poor consolidation has been obliterated by the surface damage now present or by the mortar coating which was applied during construction. However, based upon the rapid increase in concrete depth, the possibility certainly exists that less than complete consolidation was achieved in the toe area of some of the wall segments.

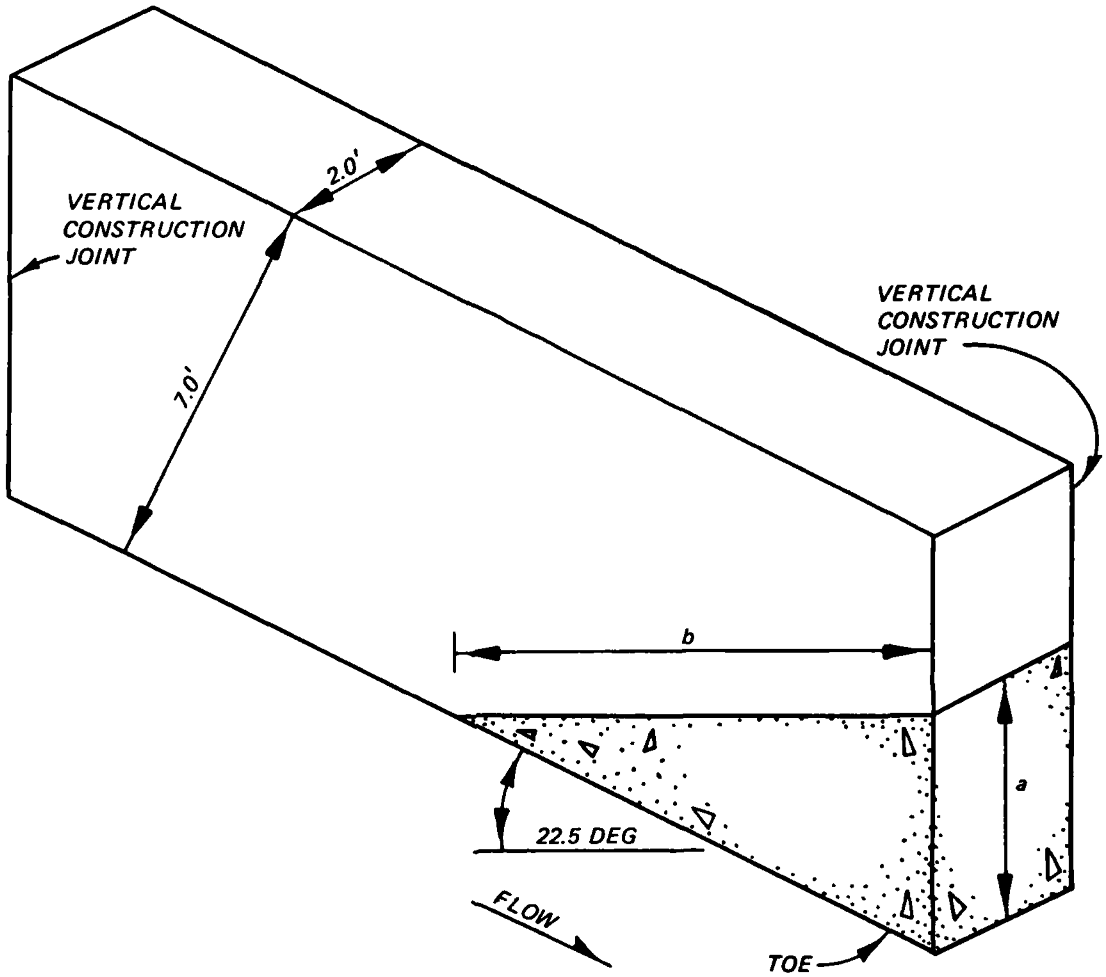


a. As-built, Dwg No. 13968-19A



b. Apparent construction

Figure 15. Warm-water chute wall construction technique



CONCRETE PLACED, CU YD	a, FT	b, FT
1	3.3	8.1
2	4.7	11.4

Figure 16. Schematic of wall section, warm-water chute. Note that concrete depth at toe builds up rapidly, making consolidation difficult

PART II: LABORATORY TESTING AND ANALYSIS

Chemical Analysis

15. Two of the concrete cores, RLP No. 2 and RLP No. 5, from Raystown Dam were analyzed for cement content and mixing water content. Two water samples taken from the reservoir were also analyzed to determine if the water would be aggressive to concrete. A sample of efflorescence was analyzed to determine its chemical composition. Samples of a similar cement paste (also Type II cement) and aggregates were tested to determine their relative susceptibilities to aggressive water attack. The report of the chemical analysis is in Appendix A.

Petrographic Examination

16. Concrete cores, aggregate particles, and a chunk sample of concrete were examined using standard petrographic techniques. The report of the petrographic examination is in Appendix B.

Acidic Water

17. Due to the nature of the concrete damage noted, acidic reservoir water was immediately suspected as a causal factor. Three sources of acidic water were postulated: (1) point sources such as manufacturing plants, etc.; (2) acidic mine runoff, a problem common in central Pennsylvania; and (3) acidic rainfall. A lowered pH of rainfall in the northeastern United States and particularly in the general area of the Raystown structure has been reported (Likens, 1976 and 1979). Data available from a collection station at Pennsylvania State University (approximately 27 miles from the Raystown structure) show the majority of rainfall pH values in the range of 3.5 to 4.5 for the period July 1977 through December 1979 (Anonymous, 1979 and 1980).

18. Baltimore District has reported that there was no indication of industrial dumping of acid upstream of the structure nor is there

any indication of mine runoff into the reservoir. While the rainfall in the area may be acidic, there is no evidence (fish or aquatic plant kills, etc.) that water quality in the reservoir is being affected. Table 4 presents pH data for the reservoir, covering 7 years. The data in this table further indicate that acidic water is not a problem at this structure.

Cement Analysis

19. Examination of cement test data developed at WES during the construction of the Raystown project revealed a Type II, low-alkali cement meeting specifications. There is nothing unusual in the test reports.

Hydraulic Considerations

20. On 20 December 1979, the situation at Raystown was discussed by MAJ Holland and Mr. Tim Fagerburg, Hydraulics Laboratory, WES, who had conducted flow tests at the structure in 1977 (Fagerburg, 1979). Two specific items were discussed:

- a. Concrete condition. Mr. Fagerburg did not recall noting a deterioration in the condition of the concrete in the warm-water chute at the time of his tests.
- b. Requirement for walls. The purpose of the walls of the warm-water chute was discussed in light of possibly not taking any repair action other than removal of the walls at some time in the future. The walls are intended to prevent the flow from diverging and thus losing velocity. Without adequate velocity, the water reaching the flip bucket would not flip into the pool but would flow over and possibly erode the rock at the end of the flip bucket. Additional model tests and tests of the soundness of the rock involved would be required to evaluate this "no repair" option.

Table 4

pH History, Raystown Reservoir

Date	Depth Sampled	pH Range
9 May 73	Surface - 100 ft	7.3-8.1
20 Jun 73	Surface - 137 ft	7.1-7.6
11 Sep 73	Surface - 140 ft	6.0-6.65
21 Mar 74	Surface - 110 ft	6.8-7.4
20 May 74	Surface - 145 ft	7.4-7.5
30 Jul 74	Surface - 150 ft	7.0-7.1
1 Oct 74	Surface - 145 ft	7.0-8.7
14 Nov 74	Surface - 145 ft	7.5-8.3
8 Jul 75	Surface - 150 ft	7.0-7.7
5 Aug 75	Surface - 150 ft	7.0-7.3
1 Oct 75	Surface - 140 ft	6.8-7.7
2 Dec 75	Surface - 145 ft	7.0-7.4
22 Apr 76	Surface - 140 ft	7.4-8.0
21 May 76	Surface - 140 ft	7.5-8.1
30 Jul 76	Surface - 100 ft	7.5-8.5
14 Jul 77	Surface - Unreadable	6.8-8.6
20 Oct 77	Surface	7.6
14 Dec 77	Surface - 145 ft	7.4 (bottom)
29 May 79	Surface - 140 ft	7.4-7.86
30 Aug 79	Surface - 180 ft	6.4-8.3

NOTES: (1) Data taken at station in reservoir near the gated spillway.
(2) Source of data: Baltimore District Water Quality Control Section.

PART III: DISCUSSION

Results

21. Following is a summary of the results of the chemical and petrographic testing performed at WES. Detailed results are presented in the appropriate appendix.

- a. The water samples which were analyzed were found to be aggressive to concrete according to the value of the Langelier Index.
- b. The efflorescence sample was found to be calcium carbonate. This is a normal product in an aggressive water environment.
- c. The cement contents of the two samples which were analyzed were lower than that specified. This is not considered significant due to the range of error in the test method used.
- d. The water-cement ratios of the cores tested were found to be close to the specified values. The differences noted would not cause a significant decrease in the strength of the concrete.
- e. Using water similar to that at the structure, solubility tests showed hydrated cement paste to be more soluble than the coarse aggregate.
- f. Examination showed etching of limestone coarse aggregate particles. Etching of paste also occurred but was less evident because the siliceous fine aggregate particles tended to remain in their original positions.
- g. There was no indication of any alkali-carbonate or alkali-silica reaction.
- h. Examination of prepared interior concrete surfaces showed none of the etching evident on exterior surfaces.
- i. All concrete appeared to be air entrained. There was a large difference between cores: RLP No. 1 (9.5 percent) and RLP No. 4 (2.8 percent).
- j. Examination of thin sections and X-ray diffraction patterns of cement paste from surface and interior concrete revealed and confirmed carbonation of cement in the surface concrete to a depth of about 1/4 in.
- k. Composition and appearance of interior concrete was normal.

Conclusions

22. The surface deterioration of the concrete in the warm-water chute is due to the dissolving away of soluble cement paste and carbonate coarse aggregate by an aggressive liquid. The water in the reservoir is capable of producing and is believed to be the cause of the damage noted. There is no evidence that acid contamination is being introduced into the reservoir.

23. The apparent preference of the water to attack the coarse aggregate, as noted by visual inspection, was not supported by chemical analysis. Rather, the paste tested was significantly more soluble than the aggregate particles tested. Additional testing would be required to resolve this discrepancy.

24. The damage is clearly related to the quantity of water flowing over the concrete. Mere contact with the water (the upstream face of the structure) does not cause visible damage.

25. A system of contiguous voids apparently exists under portions of the walls of the warm-water chute near the shear key. The rate at which damage is occurring on the concrete surface, as determined from depressions on samples examined in the laboratory (1/4 in. in approximately 10 years), makes it doubtful that the damage noted inside and under the walls is entirely due to the aggressive water. Instead, the voids are probably the result of a combination of the design of the walls which allowed the aggressive water access to the interior of the walls and inadequate consolidation which gave the aggressive water greater surface area to act upon. For the water to have acted on properly consolidated concrete to create the voids seen would have required a rate of paste and aggregate removal inside the walls much higher than that seen on the outside of the wall, which is extremely unlikely.

26. The option of taking no repair actions and ultimately removing the walls of the warm-water chute may be valid. This approach would require additional hydraulic and materials testing before a decision could be made.

Recommendations

27. The economics of investigating the no-repair option should be considered in regard to the anticipated costs to repair the walls of the warm-water structure.

28. If the decision to repair the walls is made, the following will be required:

- a. The contiguous voids within and under the walls of the warm-water chute near the shear key, whether created by the action of the aggressive water or by inadequate consolidation or both, should be located and filled to prevent further interior deterioration of the concrete. WES can provide assistance during both the locating and the grouting processes.
- b. All damaged surface areas should be coated with a properly formulated compound to prevent further deterioration. WES can also provide assistance in selecting and applying the wall coating.

29. In either case, all areas of the structure which are subjected to large water flows should be inspected to determine the full extent of surface damage. Some areas, such as the walls and ceiling of the warm-water tunnel, may require repair even if the walls of the chute are not repaired.

30. Determination of the relative aggressiveness of the reservoir water should be included in the design stage of future projects to allow for inclusion of preventative measures, if required.

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APPENDIX A: CHEMICAL ANALYSIS OF CONCRETE, WATER, AND EFFLORESCENCE SAMPLES

Cement Content and Mixture Water

1. Two concrete cores, RLP No. 2 and RLP No. 5, from Raystown Dam were analyzed for cement content and mixing water content. The cement content was determined by the (Tabikh, et al; 1972)* method and checked by the Florentin Method (The Chemical Commission of the CETIC; 1973). The mixing water content was determined by a method obtained from the Portland Cement Association. The test results are shown in Table A1.

2. The cement content and mixing water content for core RLP No. 2 was found to be 465 lb cement and 212 lb water per cu yd, with a water-cement ratio of 0.46. The cement content and mixing water content for core RLP No. 5 was found to be 429 lb cement and 171 lb water per cu yd, with a water-cement ratio of 0.40.

3. Mr. Arthur Fleetwood, Baltimore District, reported by telephone the concrete mixture proportions to MAJ Holland, WES. Two concrete mixtures were used in making the walls. Mixture 1A was to contain 517 lb cement and 243 lb water per cu yd. Mixture 1B was to contain 494 lb cement and 232 lb water per cu yd. The average cement content of the two concrete mixes is 505 lb cement per cu yd, and the water-cement ratio for both mixes is 0.47.

4. The cement contents of the two cores tested were less than the specified amount of cement. Core RLP No. 2 was found to contain 40 lb of cement less than the specified amount, and core RLP No. 5 was found to contain 76 lb of cement less than the specified amount. The water-cement ratio for core RLP No. 2 was found to be nearly the same as the specified water-cement ratio; however, core RLP No. 5 was found to have a water-cement ratio somewhat lower than the specified water-cement ratio.

Chemical Analysis of Water

5. Two water samples from Raystown Dam Reservoir were obtained for analysis:

Sample No. 1. From upstream channel leading to structure, approximately 1 ft below surface.

Sample No. 2. From downstream, across stilling basin from structure, 1 ft below surface.

6. The pH of sample No. 1 and the temperature of both samples were determined when the samples were taken. The pH of sample No. 1 was 7.95, and the temperatures for sample No. 1 and No. 2 were 25°C and 24°C, respectively.

* References cited are listed alphabetically in the list of references following the main text.

7. The samples were analyzed and the results are shown in Table A2. The two samples were found to be nearly identical, as indicated by the analysis. The Langelier Index values for the two waters were calculated. The pH of the water taken in the field and the pH taken at the laboratory were used in calculating the Langelier Index value. The values for the two water samples were -1.12 when using the laboratory pH and -0.67 when using the pH taken in the field. A negative index indicates that the water is aggressive and will remove lime from the concrete.

Analysis of Efflorescence Sample

8. A sample of the efflorescence which was taken from the upstream wall under the right spillway was analyzed. The sample was dried to a constant weight at 105°C and analyzed. The test results are shown in Table A3.

9. The efflorescence sample was found to be calcium carbonate. Lime leached from the concrete by water is converted to calcium carbonate in the presence of moisture and carbon dioxide in the air. The water which was found to be aggressive would remove some lime from the concrete, and this lime would be converted to calcium carbonate.

Solubility of Limestone and Cement Paste

10. Three samples of the limestone aggregate from the cores were obtained by drilling into the limestone aggregates of different colors. The limestone powder obtained by drilling was then ground to pass a 150-μm (No. 100) sieve and designated as limestone samples A, B, and C. A cement paste made from a Type II portland cement which had aged for 10 months was ground to pass a 150-μm (No. 100) sieve.

11. The solubility of the limestone samples and the cement paste was determined by placing 0.50 g of each into 500 ml of a simulated water made in the laboratory, which had a pH similar to that of the reservoir water and contained approximately the same amount of calcium, magnesium, and total dissolved solids. The sample and simulated water were placed on a magnetic stirrer and stirred for 4 hr, then filtered. The filtrate was analyzed for calcium and magnesium using an atomic absorption spectrophotometer. The amount by weight of limestone sample A and the cement paste soluble in the simulated water was determined gravimetrically by filtering through a tared Gooch crucible containing two glass filter papers. The test results are shown in Table A4.

12. The cement paste was found to be significantly more soluble in the simulated water than the samples of limestone, as indicated by the analysis.

Conclusions

13. The two water samples that were analyzed were found to be aggressive to concrete, as indicated by the negative value of the Langelier Index.

The aggressive water would dissolve the hydrated cement paste, and this would contribute to the pitted condition of the concrete surface at Raystown Dam.

14. The efflorescence sample was found to be calcium carbonate. Presence of calcium carbonate deposits would be expected in an aggressive water environment.

15. The cement contents of the two cores analyzed were found to be 465 and 429 lb cement per cu yd. These values were lower (40 and 76 lb) than the specified cement content, 505 lb per cu yd. These low cement contents would not be considered significant, since the testing and sampling error for determining cement contents is approximately 50 lb of cement per cu yd.

16. The water-cement ratios of the two cores tested were found to be 0.46 and 0.40, which is close to the specified value of 0.47, and would not have caused any significnat decrease in the strength of the concrete.

17. The apparent preference of the water to attack coarse aggregate rather than paste is not supported by the relative solubilities of the two materials as tested in the laboratory.

Table A1

Cement Content and Mixing Water Content for Raystown Dam Cores

Concrete Core	Cement lb/cu yd	Mixing Water lb/cu yd	Water-Cement Ratio by wt
RLP No. 2	465	212	0.46
RLP No. 5	429	171	0.40

Table A2

Analysis of Water Samples from Raystown Dam

Sample	pH*	Total Dissolved Solids, mg/l	Alkalinity as $CaCO_3$, mg/l	Hardness as $CaCO_3$, mg/l	Calcium mg/l	Magnesium mg/l
No. 1	7.5	117	47	68	17.4	5.1
No. 2	7.5	115	46	68	17.7	5.1

Sample	Langelier Index (laboratory pH)	Langelier Index (field pH)
No. 1	-1.12	-0.67
No. 2	-1.12	-0.67

* pH determined at laboratory.

Table A3

Test Results for Efflorescence Sample

	%
Ignition loss, 900°C	44.1
CaO	55.0
$CaCO_3$*	99.1

* Based on ignition loss and CaO content.

Table A4

Solubility of Limestone Aggregate and Cement Paste

	AA Analysis	
Sample	Ca mg/l	Mg mg/l
Limestone A	20.2	4.0
Limestone B	22.0	4.0
Limestone C	21.0	4.1
Cement Paste	118.4	3.2
Simulated Water	17.9	4.0

Gravimetric Analysis

Sample	% Soluble in Simulated Water
Limestone A	0.80
Cement Paste	14.41

APPENDIX B: PETROGRAPHIC REPORT

Samples

1. Seven concrete samples were received from the U. S. Army Engineer District, Baltimore, on 14 September 1979 for examination and testing to determine the cause of deterioration and the quality of the concrete from the warm-water chute at Raystown Dam. Several loose coarse aggregate particles were obtained from MAJ Terence C. Holland after his inspection of Raystown Dam during 28 through 30 August 1979.

2. The concrete samples are described below:

Field Serial No.	Sample Description
RLP No. 1	6-in. diameter concrete core
RLP No. 1a	3-1/4-in. diameter concrete core; this was a smaller diameter continuation of RLP No. 1.
RLP No. 2	3-1/4-in. diameter concrete core representing the best concrete seen by MAJ Holland during his visit to the project.
RLP No. 3	3-1/4-in. diameter concrete core taken across a vertical floor joint.
RLP No. 4	3-1/4-in. diameter concrete core.
RLP No. 5	3-1/4-in. diameter concrete core.
No Number	Rectangular concrete fragment, 8-in. by 5-in. by 3-3/4 in.; location was near to core RLP No. 4.

Cores 1, 1a, and 3 were taken vertically from the floor of the warm-water chute. Cores 2, 4, and 5 were taken horizontally from a wall of the warm-water chute.

Test Procedure

3. All the samples of core were examined and logged; the fragment of concrete was examined.

4. Samples RLP No. 2 and RLP No. 5 were selected for cement content determination by CRD-C 30-67 (U. S. Army Engineer Waterways Experiment Station; 1949).* The results of that test are provided in Appendix A.

* References cited are listed alphabetically in the list of references following the main text.

5. Samples RLP No. 4, RLP No. 1, and the concrete fragment were sawed and ground smooth. These smoothed surfaces and exterior formed surfaces from the same samples were examined with a stereomicroscope.

6. When this examination indicated significant differences in air contents between two samples (RLP No. 1, RLP No. 4), this difference was verified by measuring the air contents using an abbreviated version of CRD-C 42-71 (U. S. Army Engineer Waterways Experiment Station; 1949).

7. The other sawed surface of sample RLP No. 4 was etched in dilute hydrochloric acid for 20 minutes. The features of this pitted surface were then compared with the concrete surfaces typical of much concrete in the warm-water chute.

8. Thin sections were prepared from the near surface concrete of samples RLP No. 1 and the concrete fragment. These sections were impregnated with an epoxy resin containing a fluorescent dye. The finished sections were examined with a petrographic microscope using a mercury lamp which provided a suitable wavelength of light to excite the fluorescent dye.

9. A cement paste concentrate was prepared from the near surface concrete and also of the interior concrete in samples RLP No. 1 and the concrete fragment. These paste concentrates were then examined by X-ray diffraction.

10. Portions of three coarse aggregate particles were drilled from sample RLP No. 1a with a small diameter core drill for examination. These samples were ground to pass a 45-μm (No. 325) sieve and were examined by X-ray diffraction to determine the mineralogical composition of the coarse aggregate.

11. All X-ray patterns were made with an X-ray diffractometer using nickel-filtered copper radiation.

Results

12. Initial examination of the concrete samples indicated etching of the limestone coarse aggregate particles to depths of 1/16 in., as indicated in Plates B1-B6 and Photo B1. The concrete represented by the concrete fragment was similar to the cores; etching of the coarse aggregate was up to 1/8 in. deep on its surface. Etching of the cement paste had also occurred but was less evident because the siliceous fine aggregate particles tended to remain in their original positions as a skeletal framework. This is shown by Photo B2. Photo B3 shows a closeup view of the etched appearance of a carbonate coarse aggregate particle from this concrete; this is one of the particles brought back from the left wall of the warm-water chute by MAJ Holland. Photo B4 shows a sawed surface of core RLP No. 4 that was etched in the laboratory for 20 minutes with dilute hydrochloric acid. There is a similarity between this effect and that shown in Photos B1-B3.

13. Breaks in the concrete cores were considered to be new ones that were due to the drilling operation. The concrete contained dark limestone coarse aggregate with a maximum size of 3 in. The fine aggregate was a natural siliceous sand (Plates B1-B6).

14. There was no indication of any alkali-carbonate rock reaction. None of the coarse aggregate particles showed reaction rims and no cracking was detected in any of the concrete samples that could be attributed to this type of reaction.

15. Examination of the sawed and smoothed surfaces representing the interior concrete of cores RLP No. 1 and No. 4 and of the concrete fragment indicated concrete in normal condition. There was none of the preferential removal of coarse aggregate that was apparent on exterior surfaces. This verified that the phenomenon was a surface one rather than a deep-seated one.

16. While all of the concrete appeared to be air entrained, the large difference in amount noted in cores RLP No. 1 and No. 4 was verified by the micrometric determination that was made. Core RLP No. 1 contained 9.5 percent air and core RLP No. 4 contained 2.8 percent air.

17. Examination of thin sections of core RLP No. 1 and the concrete fragment indicated normal concrete. There was carbonation of the cement paste from the concrete surfaces inward to a depth of about 1/4 in., and the paste to this depth appeared more porous due to greater penetration of the fluorescent dye into this area.

18. X-ray diffraction patterns of cement paste concentrates from near surface and interior portions of core RLP No. 1 and the concrete fragment showed the paste to consist largely of ettringite, calcium hydroxide, tetracalcium aluminate carbonate-11 hydrate (monocarboaluminate), quartz, and calcite. The quartz and calcite were largely due to aggregate contamination. The other three compounds are normal constituents of hydrated portland cement. While calcium silicate hydrate was also present, it is not usually recognizable because of its poor crystallinity. The most significant difference between samples or between areas within samples was that the calcium hydroxide was less plentiful in the near surface samples. This absence or conversion of calcium hydroxide to calcium carbonate (calcite) agrees with the carbonation of cement paste in this area that was seen in the thin sections. No ettringite was detected in the near surface cement paste from the concrete fragment.

19. Three aggregate particles were examined by X-ray diffraction; all were dolomitic limestone composed mainly of calcite with some quartz and some dolomite. One piece also contained a little clayey material which was kaolinite and clay-mica.

Discussion

20. No evidence of deleterious alkali-carbonate or alkali-silica reactions was found. While the concrete surfaces showed a pitted appearance due to removal of coarse aggregate, this condition was not present in the interior of the concrete; the composition and appearance of interior concrete was normal for such material. The unusual surface appearance was due to dissolving away of soluble cement paste and soluble carbonate coarse aggregate by an aggressive liquid. Since the presence of acid in the water was not indicated by chemical tests,* this suggested the water itself might be attacking the cement paste and the limestone aggregate. Calculations of the Langelier Index (Buck, Mather, Thornton; 1967) indicated the lake water would be agressive.* This calculation takes account of water composition, temperature, and pH to determine whether water will dissolve or deposit lime during contact with hydrated cement paste. Chemical tests* of powdered carbonate coarse aggregate from this concrete and of powdered hydrated portland-cement paste, a laboratory specimen, using water like that in Raystown Lake, indicated the paste was more soluble. Inspection of the concrete surfaces would lead one to think the carbonate rock was more soluble since it has dissolved away below the level of the original surface. However, as mentioned earlier, the framework of siliceous sand grains tend to stay in place as cement paste is removed. Observations of color changes of the cement paste on sawed surfaces, increased porosity of surface cement paste in thin sections, and depletion of calcium hydroxide near concrete surfaces by X-ray diffraction examination all suggest alteration of the cement paste to a depth of perhaps 1/4 in., whereas removal of the carbonate coarse aggregate appears to be more like 1/16 to 1/8 in.

21. These considerations indicate that the water of Raystown Lake is aggressive to hydrated portland cement paste and to carbonate rock and that this aggressive action could produce the effects seen on concrete surfaces in the field.

Conclusions

22. The pitted condition of concrete surfaces at Raystown Dam, especially in the warm-water chute, is due to solution and removal of hydrated cement paste and carbonate coarse aggregate by an aggressive liquid to depths of 1/4 in.

23. Since the presence of acid in water appears unlikely, it is believed that the water itself is the aggressive agent since calculation of the Langelier Index of the water shows that it would be aggressive.*

24. Since the effect of this attack of concrete surfaces is approximately 1/4 in. in about 10 years time, these data can be used to make rough extrapolations of probable future rates of attack.

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* See the portion of the overall report covering chemical results.

25. The surface attack of concrete due to aggressive water was limited to a depth of approximately 1/4 in. and thus was not responsible for the areas of larger voids and drummy concrete described in other parts of the report.

Photo B1. Top surface of core RLP No. 5 showing preferential etching of carbonate coarse aggregate (X1.2)

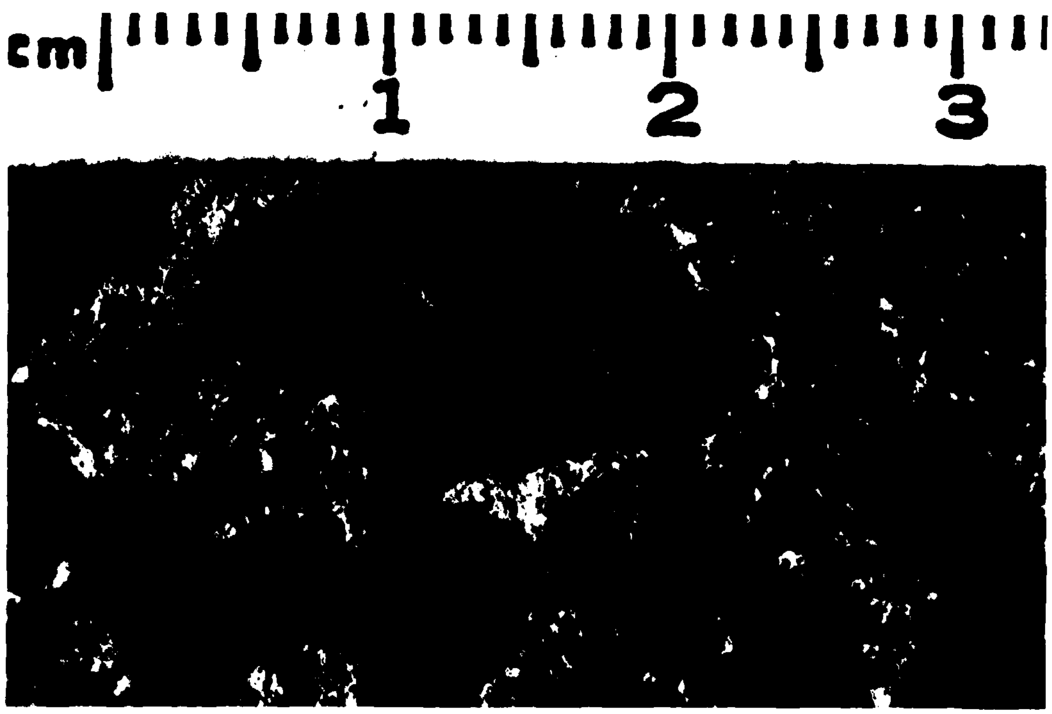
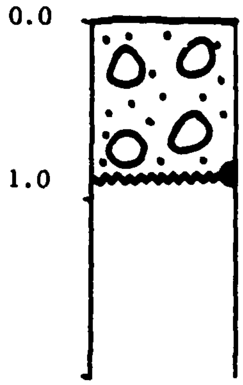


Photo B2. Enlargement of lower portion of previous picture. The siliceous fine aggregate and the nonsoluble portions of the coarse aggregate remain in relief while soluble material has been removed (X4.1)

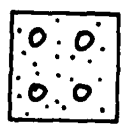
Photo B3. Carbonate coarse aggregate particle provided by MAJ Holland. Appearance is that of an acid-etched limestone particle (X1.7). The particle came from a hole in the left wall of the warm-water chute.

Photo B4. Sawed surface of core RLP No. 4 that was etched in dilute hydrochloric acid for 20 minutes (X1.1). Compare with previous photos

Depth, ft



Top surface essentially as formed with etching of limestone coarse aggregate particles up to 1/16 in. deep.
New break at 0.95 ft. End of core.
Limestone coarse aggregate, about 3-in. maximum size.
Steel reinforcing bar about 7/8-in. diameter at bottom of core.
Air content by CRD-C 42-71 (U. S. Army Engineer Waterways Experiment Station; 1949) was 9.5 percent.

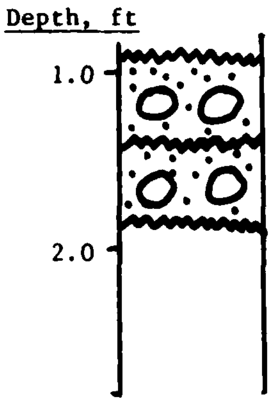


Concrete

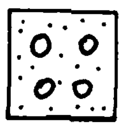
1 in. = 1 ft
(No width scale)

Raystown Dam
6-in.-Diameter
VERTICAL CONCRETE CORE
FROM FLOOR
RLP No. 1

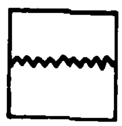
PLATE B1



Top is at 0.95 ft; this is a smaller diameter continuation of core RLP No. 1.
New breaks at 0.95, 1.2, and 1.9 ft.
Limestone coarse aggregate, about 3-in. maximum size.



Concrete

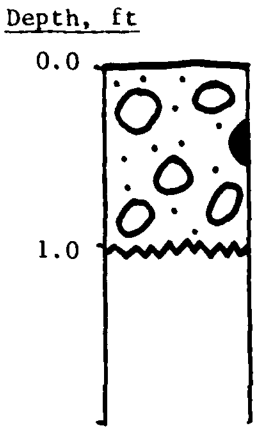


Fracture

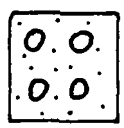
Raystown Dam
3-1/4-in.-Diameter
VERTICAL CONCRETE CORE
FROM FLOOR
RLP No. 1a

1 in. = 1 ft
(No width scale)

PLATE B2



The outer end is the roughened original surface. The limestone coarse aggregate particles are etched to a depth of about 1/16 in.
Imprint of large reinforcing bar (~1-1/4-in. diameter) at 0.4 ft.
New break at 1.05 ft. End of core.
Limestone coarse aggregate, about 3-in. maximum size.


Concrete

1 in. = 1 ft
(No width scale)

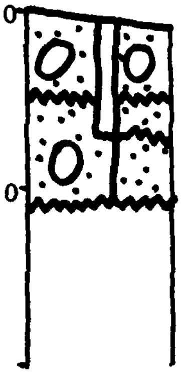
Raystown Dam
3-1/4-in.-Diameter
HORIZONTAL CONCRETE CORE
FROM WALL
RLP No. 2

PLATE B3

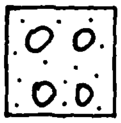
Depth, ft

0.0

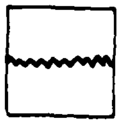
1.0



Core taken across a slotted open vertical joint; slot was about 3/4 in. wide. One side of the slightly sloping top had etched limestone coarse aggregate while the other did not.
Slot was lined with black tarpaper and had contained a piece of solid black rubber tubing about 5/8 in. thick and a strip of gray rubber.
The breaks at 0.55, 0.7, and 1.1 ft were new.
Limestone coarse aggregate, about 3-in. maximum size.



Concrete

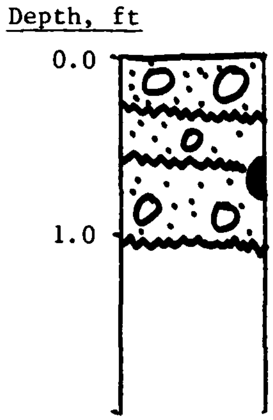


Fracture

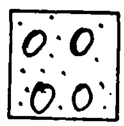
Raystown Dam
3-1/4-in.-Diameter
VERTICAL CONCRETE CORE
FROM FLOOR
RLP No. 3

1 in. = 1 ft
(No width scale)

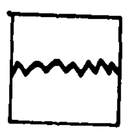
PLATE B4



The outer end is the roughened original surface with the limestone coarse aggregate etched to a depth of about 1/16 in.
New breaks at 0.3, 0.6, and 1.05 ft; the last one is the end of the core.
Large diameter (1-1/2 in.) reinforcing steel bar at 0.6 ft.
Limestone coarse aggregate about 3-in. maximum size.
Air content by CRD-C 42-71 (U. S. Army Engineer Waterways Experiment Station; 1949) was 2.8 percent.



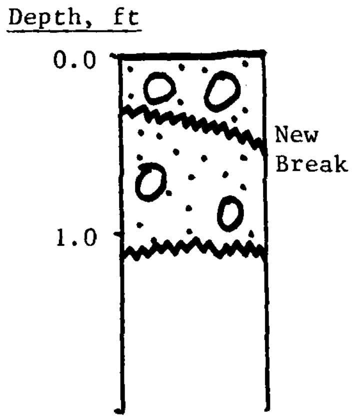
Concrete



Fractures

1 in. = 1 ft
(No width scale)

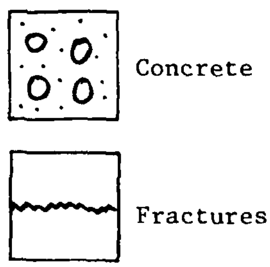
Raystown Dam
3-1/4-in.-Diameter
HORIZONTAL CONCRETE CORE
FROM WALL
RLP No. 4



The outer end is the roughened original surface with the limestone coarse aggregate particles etched to a depth of about 1/16 in.

New break at 1.1 ft. End of core.

Limestone coarse aggregate, about 3-in. maximum size.



Raystown Dam
3-1/4-in.-Diameter
HORIZONTAL CONCRETE CORE
FROM WALL
RLP No. 5

1 in. = 1 ft
(No width scale)

PLATE B6

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Holland, Terence C
  Concrete deterioration in spillway warm-water chute Raystown Dam, Pennsylvania / by Terence C. Holland ... [et al.]. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1980.
  32, [12] p., [3] leaves of plates : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; SL-80-19)
  Prepared for U. S. Army Engineer District, Baltimore, Baltimore, Md.
  References: p. 32.

1. Concrete deterioration. 2. Concrete erosion. 3. Raystown Dam. 4. Spillways. I. United States. Army. Corps of Engineers. Baltimore District. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; SL-80-19.
TA7.W34m no.SL-80-19

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